515

VOLUME 80 SEPARATE No. 515

PROCEEDINGS

AMERICAN SOCIETY
OF
CIVIL ENGINEERS

OCTOBER, 1954

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SOIL MECHANICS AND FOUNDATIONS
DIVISION

{Discussion open until February 1, 1955}

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Printed in the United States of America

Headquarters of the Society
33 W. 39th St.
New York 18, N. Y.

PRICE $0.50 PER COPY

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This paper was published at 1745 S. State Street, Ann Arbor, Mich., by the American Society of Civil Engineers. Editorial and General Offices are at 33 West Thirty-ninth Street, New York 18, N. Y.

ENGINEERING PROBLEMS IN COLUMBIA BASIN VARVED CLAY

Fred C. Walker[1], M. ASCE, and W. H. Irwin

SYNOPSIS

In many places clay deposits are found which have definite laminated structure. The individual layers or varves represent seasonal deposition in lakes resulting from annual inflows. Consequently each separate layer contains a wide range of grain sizes, but exhibits a gradation from coarsest grains near the base of the layer to finest near the top. The Nespelem deposits are predominantly of this type and were developed during the end of the last Glacial Era when the Columbia River was dammed by ice and its flow diverted through high level channels such as the Grand Coulee. The Nespelem deposits are therefore confined to the pond created by the glacial dam. The thinness of the layers and their total depth indicate that sedimentation in this pond continued for many hundreds of years and produced a material that has had a profound effect on engineering problems in this area.

Undisturbed deposits show some of the characteristics of sedimentary rocks but, once disturbed, they reassume all the worst engineering characteristics of freshly deposited alluvial and lacustrine clays. As a consequence, test results both in the field and the laboratory are very deceptive. The varved nature of the undisturbed materials, the occurrence of old landslides, and the usually saturated condition of both disturbed and undisturbed materials make the testing and interpretation of results extremely difficult.

Once the ice dam was removed, the river entrenched itself into these valley deposits, leaving oversteepened slopes along the sides of the valley with treacherous combinations of undisturbed deposits, landslide debris, and reworked sediments. Landslides continue to be of frequent occurrence. Overburden excavation for Grand Coulee Dam and the new high water levels of the reservoir activated many slides. These entailed many difficult construction problems and right-of-way problems along the reservoir rim.

The solution of the engineering problems of structures founded in varved clays has run the entire gamut of accepted practice and has required the introduction of considerable ingenuity in the solution of specific cases. These range from freezing the material in place, through minimizing disturbance of the deposits, to avoidance, loading or unloading, and various types of drainage including taking advantage of subsurface bedrock configuration and gravel zones.

Experiences with the Nespelem varved clays have served to

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emphasize the deficiencies in classical design and testing procedures. In particular they have demonstrated the need for thorough and critical appraisal of the nature of such soils using to the utmost the arts of Geology and Soil Mechanics in evolving solutions to engineering problems. These experiences have also served to develop a procedure for the analysis of other types of foundations now generally followed by the Bureau of Reclamation.

INTRODUCTION

The Nature of Varved Clays

In many places in the world clay deposits are found in which the clay being sedimentary in origin, has a definite bedded structure. Many such sedimentary clay deposits were formed in lake basins characterized by cyclic changes in sedimentation environment. Clay deposits, in which cyclic sedimentation has produced a repetition of layering and internal structure, have commonly been called "varved" clays. The peculiar combination of geologic, topographic, and climatic factors which produce the required rhythmic sedimentation conditions is most commonly found accompanying the advance and retreat of glacial ice. Consequently, most varved clay deposits are glacial in origin and are found in and adjacent to areas which have been glaciated.

Although varved clay behaves according to some of the general rules of soil mechanics as other clay materials, special features in its geologic origin, structure, composition, or relation to adjacent deposits of other materials results in abnormal or anomalous test data. The abnormality may not be appreciated until, during construction operations, the clay fails to behave as predicted. Advance knowledge that a clay deposit is varved and of glacial origin can therefore be utilized to warn the engineer and geologist that special field and laboratory investigations are required, and that special weaknesses and characteristics of the clay, unless properly evaluated, results in unsuitable designs or costly interruptions in construction schedules. Fortunately, varved clays are easily recognized as such and, utilizing the finding of prior investigators, the Bureau of Reclamation has developed special testing and design, as well as construction criteria during the course of engineering work in the Columbia River area where varved clays are widespread.

Varved clays can be easily distinguished from other layered lacustrine deposits of clay by the following characteristics: (1) the successive layers or beds are thin but remarkably constant in thickness, varying in any one deposit within a rather narrow range; (2) each layer shows a consistent internal gradation in grain size from coarsest sizes at its base to finest sizes at its top; (3) the layers occur in pairs in which the grain sizes in the lowermost silt layer grade continuously to the finer sized particles in the overlying clay layer; (4) the top of the clay layer in each pair is sharply separated from the bottom of the overlying silt layer by the sharp change in grain size from clay to silt. Each pair of layers is referred to as a varve and commonly interpreted as the material deposited in the lake basin during 1 year. The "annual" significance of the varve is of no interest to the practicing engineer, but

the structure and therefore its origin is important to the decisions he must make on design and construction procedures.

Disruption of normal drainage is a common accompanying characteristic of glaciation. Thus, lake basins may be formed by ice masses advancing across and blockading main lines of drainage; the blockade or dam may be due either to the ice mass itself or to the material—silt, sand, gravel, and boulders—transported and released by the melting of the ice. Although such lake basins are generally temporary, they may, from a geologic point of view, last for hundreds of years. While in existence, the lakes serve as catchment basins for the products yielded by normal weathering, erosion, and stream transportation, as well as the variety of rock materials released by the melting ice. Following the normal rules of sedimentation, the coarsest materials, such as sand and gravel, are deposited as deltas at the mouths of streams entering the lake basins. The finer material is dispersed throughout the lake water and falls to the bottom to form the successive layers of silt and clay.

Diffusion of the suspended load through the area of the lake, undoubtedly aided by thermal conditions, and the setting rate of different sized particles combines to produce the continuous gradation within each layer-pair or varve. Particles in the silt-size range settle during the more turbulent water periods of spring and summer; finer clay fractions settle chiefly during winter period when the water is quiet. The spring breakup of ice on the lake typifies the annual climatic change during which renewed flows of water from melting glacial ice and increased sediment loads combine to abruptly shift the sedimentation back to coarse particles and produce the sharp demarcation between successive layer-pairs or varves.

The Geology of the Nespelem Varved Clays

Origin and Distribution of the Deposits

The Nespelem Formation, predominantly a glacial-lacustrine deposit of the varved clay type, is found chiefly in the Columbia River Valley and its tributaries in north central and northeastern Washington. Although the Nespelem deposits extend for several hundred miles along the valley of the Columbia River and related deposits are found in British Columbia, the varved clays which have been the focal point of the Bureau of Reclamation's studies are those in the vicinity of the Grand Coulee Dam and within its reservoir—Lake Roosevelt.

Grand Coulee Dam is situated on the Columbia River in north central Washington, about 70 air miles west of Spokane and 150 miles east of Seattle. Lake Roosevelt extends up the Columbia River Valley for about 156 miles to the International Border. The Columbia River at Grand Coulee Dam and for a considerable portion of its path has a sinuous course along the northern margin of the Columbia Lava Plateau. Its canyon-like valley ranges up to 1,500 feet in depth and, for a portion of its course, charts the boundary between the essentially flat-surfaced horizontal basalt flows of the Columbia Plateau to the south and the complex granitic mountains to the north.

The Nespelem Formation, essentially glacial in origin but with

important fluvio-glacial components was formed during the last phases of the Pleistocene Epoch when the Columbia River was dammed by glacier ice. This obstruction to the normal flow of the river occurred some miles downstream from Grand Coulee Dam in the area where the Okanogan Ice Lobe, moving southerly down the Okanogan River Valley, crossed the valley of the Columbia River. At its maximum development, the ice sheet extended southward on the Columbia Lava Plateau a distance of some 30 miles or more south of the Columbia River and extended eastward upstream for several miles past the site of the present Grand Coulee Dam. The lake thus formed served as an extensive clarifying or quiet-water basin in which large volumes of silt and clay carried by the glacial melt water were trapped. Although short-lived as Geologic Time is measured, the lake must have existed for several thousand years for at Grand Coulee Dam more than 800 feet of varved and stratified Nespelem deposits were formed.

During the period of displacement of normal Columbia River drainage the overflow of the glacial lake escaped southwestward across the southern rim of the valley at numerous points cutting a variety of channels into the gently undulating surface of the basalt plateau. Grand Coulee, the largest of these channels, heads in the south wall of the Columbia River Valley about a mile south (upstream) from the site of Grand Coulee Dam. The Grand Coulee channel was the major outlet for the overflow from the pond, and its bedrock floor (basalt and granite) is partially covered by deposits of boulders, gravel, and sand.

During the last stages of ponding and decay of the ice dam, the main flow of the Columbia River gradually abandoned the Grand Coulee Channel and resumed its normal course down the Columbia River Valley. For a very brief period, an arm of the lake characterized by sluggish currents to essentially quiet-water conditions extended down through the Upper Grand Coulee for a distance of approximately 25 miles. As a result poorly varved to stratified Nespelem silt was deposited as a thin veneer over the sand and gravel in the Upper Grand Coulee coincident with the last phases of silt deposition in the main body of the glacial lake in the Columbia River Valley.

The most conspicuous topographic feature of the Nespelem deposits in the Columbia River Valley is the Nespelem Terrace. Its surface represents the lake bottom at the time when the Columbia River abandoned the Grand Coulee route and returned to its present course. At various elevations below the level of the Nespelem Terrace are discontinuous benches and terraces commonly veneered with gravel, which were formed as the river cut down through the Nespelem to its present level.

In general, the Nespelem deposits, consist predominantly of compacted, perfectly varved clay and silt grading up through poorly varved into relatively little compacted, stratified, lacustrine silt. Adjacent to the valley walls, beds of sand and gravel finger into the clay and silt and represent the coarser materials swept into the lake from side valley drainage. In a few localities, the lower varved clays are separated from the upper stratified silts by a zone of glacial till. In such areas, the early-formed varved deposits were actually overridden by the advancing ice; as the ice melted, material ranging from large boulders to gravel and sand were dumped to form a zone of the unsorted debris typical of a

glacial till. Lenses of poorly stratified silt, sand, and gravel, locally intermingled with the till, represent the imperfect sorting accomplished by melt-water streams running along the side or at the base of the ice. The till zone is present in the Nespelem deposits of the San Poil River Valley (San Poil Ice Lobe) and in the main Columbia Valley at the mouth of the San Poil Valley, as well as downstream from Grand Coulee Dam.

In a strict geologic sense, the Nespelem varved silt and clay as a late glacial lacustrine valley fill restricted to the area of the Columbia River Valley and its tributaries occupied by the glacial lake. Small but locally important proportions of the nonlacustrine materials referred to above are generally included as part of the Nespelem deposits. During the transition period from glacial lacustrine to normal river conditions, considerable volumes of stratified silt, sand, and gravel were deposited along the ice front within the confines of the invading lake as well as upon the flanks of the valley adjacent to the lake basin. Thus, at Grand Coulee Dam deposits of stratified silt and sand lie on and above the Nespelem lake deposit and in re-entrants and ravines in the valley sides. Their behavior and handling is frequently linked with that of the varved, lacustrine phases of the deposit.

Structure of the Varved Clays

As further background for the engineering problems presented in this paper, certain structural and compositional features of the Nespelem deposits are presented. These materials, as exemplified by the sequence at Grand Coulee Dam, can be divided into three major groups: (1) a lower zone of predominantly varved silt and clay overlain by; (2) an intermediate zone of till and poorly sorted silt, sand, and gravel overlain by; (3) an upper zone of poorly varved to stratified lacustrine clay and silt and minor amounts of fluvial sand and gravel.

This sequence presents in a general sense many of the important elements characterizing the fill at other locations downstream from the dam and upstream in the reservoir area. Absence of some members, such as the till, due to nondeposition or erosion and variations in thickness of varved clay, stratified silt and sand, or sand and gravel members produces wide variations in sections in different areas of the lake basin, but all show certain general similarities. Here as elsewhere in the Columbia River Basin where these deposits have been encountered in engineering work the varved clay has been the most sensitive and critical material and has required the greatest departure from normal testing and investigation procedures.

The lowermost portion of the lower zone consisted of massive silt to poorly varved clay strata interspersed with thin sand to fine gravel beds. Their chief characteristics were lack of uniformity in thickness, succession of types and internal structures. This dominant irregularity gradually gave way with the appearance higher in the section of a repeated sedimentary cycle: (1) sand, (2) massive silt, (3) varved clay. The lowest member of this three-part sequence grades up from coarse, current-bedded sand, in places gravel bearing, to fine sand. In the middle member the coarse-grained silt, frequently faintly current-bedded, grades up into fine-grained, nonstratified silt. The upper member consists of

definitely and regularly varved silt. The contacts between the three members of each sequence are generally gradational, but the sand member commonly rests with slight disconformity upon the top of the varved member of the preceding sequence. Higher in the section, the sand member decreases gradually in thickness and finally disappears entirely. The massive silt member decreases in thickness and in average grain size, with the result that the varved structure predominates. In the upper portions of the varved zone, the distinctly varved clay grades into thin-bedded laminated clay, silt, and very fine sand, with an occasional varved clay interval.

The occurrence of interbedded, poorly stratified sand and gravel marks the change to the till of the middle zone. The material of the till zone, consisting of a heterogeneous assortment of particle sizes ranging from clay to boulders typical of glacial till, is overlain predominantly by the slightly compacted stratified, lacustrine clay and silt which represents the upper zone. Where not confused by subsequent erosion or by deposition of silt, sand, and gravel from side valley drainage the flat, terrace-like top of the upper zone represents the floor of the old glacial lake at the close of the period of lacustrine deposition.

The full stratigraphic sequence represents, directly or by implication, the sequence of geologic events which gave rise to the Nespelem deposits. Thus, the lowermost portion of the varved zone represents the unsettled conditions—fluctuating stream and lacustrine—which characterized the earliest phases of blockade of the river by the advancing ice sheet. The three-part sedimentary cycle—sand, massive silt, varved clay—represent a later more stable phase in which volume of incoming sediments or depth of lake or both fluctuated rhythmically. The disappearance of the sand member and eventual predominance of the varved clays represent the final effectual blockade of the river by the ice dam and the long interval of deep water, lacustrine sedimentation.

The till zone and its related poorly stratified lenses of sand and gravel represent materials deposited directly from melting ice and, where present, prove the presence of glacial ice. At Grand Coulee Dam and in other localities, where the early formed varved clays in the lake were subsequently overridden by the glacier, the varves of the basal zone are markedly distorted and crushed in many places.

The relatively thin deposit of Nespelem silt which overlies sand and gravel in the upper Grand Coulee channel, is correlative with the late-stage, uppermost silt deposits in the Columbia Valley. In these deposits in the Coulee, the silt and clay layers are rather distinct, and, in some cases, quite sharply separated. Current bedding is much more prominently developed, as would be expected, since these deposits must have been formed at the best in very shallow water. Each pair of silt and clay layers is presumably a "varve" in the sense that they represent annual deposits. They can be distinguished with ease from the more perfectly varved materials deposited in the main lake, and in an engineering sense their most important difference is markedly less consolidation.

FIELD TESTING

Visual Identification

Drive sampling or core drilling procedures produce samples suitable for visual examination generally with minor distortion. The varved structure can best be determined by observing samples as they are allowed to dry since drying in the silty phases is more rapid than in the clay. However, even in dry cores the structure is clearly evident because the silts are lighter in color than the clays and the change in texture is also commonly apparent. Disturbed samples would be classified as ML-CL or MH-CH, but would not truly represent the actual condition of the material without supplementary notations to describe the structure of the deposit. Zones of disturbance are recognized when displaced blocks are cored in which case the lack of horizontal bedding would be evident or if exploration is performed in an area known to be definitely varved, a lack of a varved structure would indicate disturbance. In those portions of the deposit where varving is not apparent disturbance would not be so readily determinable. Superficially portions of the deposits have been reworked by wind action further complicating the description and identification of these materials. Correlation of structure is possible only within short reaches largely because good marker beds do not exist. Interpretation of foundation conditions must therefore depend to a large extent on corroborative evidence as well as examination of drill cores.

Problems Associated with Field Testing

Penetration tests show deceptively high strength for these varied clays. Tests showed up to 400 blows per foot using the usual penetration testing procedures, indicating a very high strength completely belied by evidence in the area that show the strength of these materials to be low. Permeability tests indicate a tight material and yet water table measurements are sensitive to seasonal changes. The varved structure results at times in the development of perched water tables. A most erratic water table level in holes of differing depths is indicated unless this feature is recognized.

When samples of these varved clays are secured commonly sufficient distortion occurs to influence test results although the distortion is not readily apparent. Also samples secured from critical locations frequently come from below the water table and are therefore completely saturated. If evaporation is allowed the natural characteristics are destroyed, but if it cannot be tolerated to some degree test results secured in a laboratory distant from the site are open to question. Samples secured from areas which were loaded by the glacial ice and those secured from locations near the valley walls often contain shear planes imperfectly healed that can scarcely be detected except through characteristically low test results.

In summary, it should be apparent that whereas the condition of being faced with varved deposits is readily apparent, the determination of the extent to which the basic conditions associated with such deposits have been destroyed is difficult; moreover the probable lack of

representativeness in samples secured for testing makes the interpretation of any laboratory testing open to question.

Laboratory Testing

Results of Testing

Variation in test results appears to be limited only by the number samples tested. In one suite of 286 samples, all secured from the right tailrace area, we find that dry unit weight varies from 79 to 129 pounds per cubic foot; water content varies from 0.6 percent to 40.4 percent and unconfined compressive strength varies from 0.0 to 234.7 pounds per square inch. Liquid limits vary over a range of 16 to 74 and plasticity indexes ranged from 0 to 42 in a group of 144 samples. However, all samples were found to lie in a long but very narrow band along the "A" line on the plasticity charts and specific gravity of the materials range from 2.70 to 2.75.

The principal factor influencing the test results appears to be the relative thicknesses of the silt band and the clay band of each of the group of varves included in the sample. There does not appear to be any significant variation of density or water content with depth nor does it appear to be possible to correlate unconfined compressive strength with depth or elevation. From this it is concluded that this part of the Nespelem deposit was subjected to an enormous load of ice and debris subsequent to its deposition.

Difficulties Associated with Testing

The primary difficulty in performing laboratory tests results from the high degree of saturation of the samples. Any loads applied to the sample are borne by the pore fluid and are reflected in equivalent pore pressure. Direct shear tests therefore show a high cohesive strength and little or not internal friction. Triaxial tests involving pore pressure correction are inconclusive since a range of effective loading is impossible.

Permeability testing has not been required, obviously horizontal and vertical permeability would differ greatly and both would be highly variable due to variation in proportions of silt and clay and also due to density variations.

Although the thicknesses of the varves are to the eye very persistent, sufficient variation exists to make the problem of securing duplicate samples difficult. The frequent occurrence of small shear planes or parting planes within the structure of the deposit prevent both the securing of representative samples and reliable test results.

Landslides

General Description of Landslides Associated with the Nespelem Clays

The landslide activity associated with the construction operations on the Columbia Basin Project is neither a new nor unusual occurrence. The geologic record reveals abundant evidence that landslides have

occurred repeatedly since the glacial period in which the Nespelem deposits were formed. Numerous topographic scars along the valley sides represent slides which have occurred within historic time. Exposures in recent slides and in construction excavations reveal distortion of varved structures, old slip surfaces, and other evidence that slides were common during the deterioration of the ice sheet, draining of the glacial lake, and the subsequent long period during which the river entrenched itself in Nespelem deposits. Repeated disturbance of equilibrium conditions due to rise and fall in ground-water levels, floods in the river, and the formation of oversteepened banks yielded a continual succession of landslides. In the course of fluvial erosion and deposition some of the lacustrine material was reworked to form new deposits of stratified clay, silt, and sand overlying the glacial varved materials. In addition, each new terrace cut by the river was coated with a veneer of silt, sand, and gravel, differing markedly in stability and perviousness from the underlying lacustrine and/or fluvial deposits.

Although there are extensive exposures of bedrock in the Columbia River Valley, there are also large areas in which bedrock is masked by relatively thin remnants of the Nespelem clays, as well as numerous areas in which considerable thicknesses of Nespelem clays still remain. The simple river terrace topography and the extensive exposures of undisturbed Nespelem clay visible at many points, belie the true range of stability conditions and mask treacherous combinations of undisturbed deposits, landslide debris, and reworked sediments distributed along the valley sides and floor. The human engineering operations have in one sense merely speeded up natural process of bank adjustment by creating new slopes, a new lake with fluctuating surface, and new groundwater levels—all different from the natural regimen of the area.

During the engineering operations at Grand Coulee Dam, landslides have occurred, in some instances repeatedly, in seven to eight general areas at and immediately downstream from the dam, in addition to numerous localities along the banks of the 156-mile reservoir. Reconnaissance examinations have been made from time to time of all of the landslides; the studies conducted on a number of them, particularly those in the immediate vicinity of Grand Coulee Dam, have included extensive drilling and laboratory testing, as well as precise surface surveys.

During the first few months of reservoir operation, large numbers of slides occurred along the banks; they represented the anticipated adjustments during the change from dry-land to reservoir conditions, with accompanying higher ground-water levels. During successive years, the frequency of slide action has decreased although slides still occur from time to time.

After the initial period of bank adjustment, a preliminary classification and investigation[2] of the reservoir banks with respect to slide probability was prepared to aid in determining from time to time the location

2. Mr. Fred O. Jones, Project Geologist for the Bureau of Reclamation on the Columbia Basin Project at that time, accomplished the field studies. Subsequently, as Chief, Landslide Study, Engineering Geology Division of the Geologic Survey, Spokane, Washington, he has continued more extensive and detailed research on the landslide activity.

and extent of additional right-of-way acquisition. In addition, it was recognized that a false sense of security might develop based on the belief that all of the bank adjustments had taken place, whereas, actually new slides might occur in many areas in which stability conditions were still precarious and the environment supplied a suitable trigger impulse. Desirable spots for recreational development, including local scenic trails and roads, would frequently coincide with areas of high bluffs of Nespelem clay overlooking the reservoir, which actually would be areas of considerable slide potential. A less obvious and therefore more dangerous condition would exist in areas of low banks but with steep, underwater slopes. Other sensitive areas in which evidence of old slides had dimmed might present an equal hazard.

Advantage was taken of what is, in effect, an "outdoor laboratory," in which the slides had taken place under the same general environment (both geologic and engineering), in order to provide knowledge for interpreting the behavior of these materials. A limited number of materials were involved—varved clay, sand, and gravel—and yet these materials were present in successive slides in a wide variety of combinations. Thus, a means was supplied of evaluating the location and probable extent of lands which might be subject to damage by future landslides.

Practically all of the landslides related to the construction activities have exhibited a remarkable degree of similarity in: (a) behavior of the landslide mass; (2) materials involved; (3) topographic form or slopes separating stable from unstable conditions. With one or two exceptions, the landslides have involved the Nespelem varved clays as the critically weak material. This has been found to be true regardless of the fact that, in many instances, large volumes of stratified sand and gravel and smaller proportions of interbedded, stratified silt have participated in the landslide action. The influence of sand and gravel typically low in cohesive strength, on a slide has been chiefly: (1) source of weight or "dead load"; (2) means of supplying water to the clay and silt beds. During periods of high rainfall, they act as catchment or storage masses and account for a temporary increase in the load over a potential slide area. Representing zones of easy percolation, they bring ground water into more extensive contact with the varved clays or with the slip surfaces of pre-existing slides.

With very few exceptions, the slides have been fundamentally of a simple type in which the rotational movement along a curved slide surface predominates over lateral translation. The heel, or rear portion of the slide mass tips backward and drops down while moving along the arc of the slide plane, and the toe bulges, or rises (relatively), while the mass, as a whole, moves laterally a moderate amount during the course of the rotational movement.

A few slides in which lateral translation was more predominant than rotation in the slide movement have occurred. In such instances, the uppermost and back part of the slip surface retains the curved aspect of the simple rotational slide. The toe or front portion of the slip surface may be flat or curved up, as in the rotational type, depending upon the material and the degree of obstruction to forward movement present in that particular instance. The middle portion of the slip surface may extend for some distance as a gently inclined to relatively flat, horizontal

slip surface. The zone of disturbance along the flat portion of the slip plane or "sole" of the slide is thin—ranging from 5 inches to 15 inches in observed cases—and consists of severely sheared to completely "remolded" clay and silt. (The slip-plane zone in the rotational slide type is similarly thin.) The disturbed zone is generally restricted to the same band of varves for distances as great as 50 feet to 75 feet with the immediately over and underlying varves rarely showing any evidence of distortion.

Slides of translation have occurred in only two proven instances; in both cases, the slides took place in the geologic past. In view of the perfection of varving and the extent of the Nespelem varved clay deposits and the hundreds of slides which have taken place during the construction and reservoir operations, it is surprising that the varved structure has not had a greater effect in producing a higher proportion of slides of translation.

The field examinations revealed that many natural cliff faces in Nespelem clay, such as occur along the sides of the ravines produced by natural erosion, will stand on relatively steep to near-vertical slopes to heights of 50 to 75 feet and rarely higher. Such faces generally retreat by rainwash and by progressive spalling of relatively thin face slabs along vertical settlement cracks, but may maintain their steep or near-vertical slope if the force of erosion along the ravine bottom is sufficient to carry away the debris. Such natural faces are relatively stable as long as their environment is constant, although the margin of safety against the triggering of a massive slide by sudden vibration or major changes in ground-water level is relatively small. On the other hand artificial faces with comparable heights and slopes are relatively unstable even though the Nespelem clay is in its original undisturbed state and all other environmental conditions are good. Attempts to produce such faces in areas of previously disturbed clay or high ground-water levels generally result in slides before the cut face approaches the proposed height.

The stability of a face in Nespelem clay along a river or reservoir must be judged in terms of its underwater profile as well as its above-water slope and other applicable criteria. If the base of a steep face or cut is newly submerged, such as in a reservoir, the margin of safety may be reduced to zero; it may fail at any time especially if a rapid fall in the free-water level takes place. Faces which extend below a free-water surface and whose visible portions consist of sand and gravel, present a special hazard in the area of the Columbia Basin Project. Such deposits frequently rest on varved clay or stratified silt; the presence of even a thin zone of that material in the underwater or basal portion of a cut may yield a slide potential as great as if the entire face were clay.

Field experience, substantiated by laboratory tests, has shown that undisturbed Nespelem clay has an inherent strength far greater than it will have if disturbed or remolded even a small amount. Thus, an important overlying condition which must be applied in judging the stability of any existing or proposed cut in Nespelem silt is whether or not the material has been subjected to prior landslides or other types of

disturbance. Caution must be used in applying this criterion, for experience has shown that large blocks or masses of Nespelem silt may participate in major landslide movements and move appreciable distances either vertically or horizontally, with little or no internal evidence of that disturbance. This condition has been most frequently encountered in connection with the blocks and masses in the middle and upper portions of a slide. Thus, if the surface traces or scars of a slide have been removed by erosion including the commonly disturbed material at the toe, or if the disturbed material is not visible, the evidence of past disturbance may go unnoticed or be greatly underestimated, for the presence of even a few slip planes in an otherwise apparently undisturbed mass may be sufficient to markedly reduce its stability level.

Experience on the Columbia Basin Project yielded the following rough "rule-of-thumb" in judging the stability of cuts in Nespelem varved clays:

a. To be classed as reasonably free from failure by massive landslide action, cuts in the varved clays 40 to 50 feet high or higher should be:

(1) Not steeper than 4:1, if dry

(2) Not steeper than 5:1, if the ground-water level is high or a portion of the base of the cut is below reservoir level

b. If the material involved has been disturbed then the slopes should be reduced to 5:1 and 6:1, respectively.

c. The maximum slope derived from (a) and (b) must be adjusted (usually reduced, rarely increased) by consideration of local factors such as:

(1) Geologic conditions including anticipated future ground water and reservoir surface changes

(2) Degree of assurance against slides desired

(3) Probability and nature of "trigger actions"

This general rule has been applied with considerable success on the project area in numerous instances when preliminary or approximate evaluations of slope stability or slide potentiality were sufficient; needless to say, judgment and experience played an important part in its successful application. It has been equally useful in directing attention to critical areas in which more detailed and reliable but more expensive methods of stability analysis were warranted.

Engineering and Construction Problems

In the simplest terms, all engineering problems in soil mechanics reduce to answering three questions: (1) how much load can the foundation support; (2) how steep can slopes safely be made; (3) how watertight are the materials? Supplemented to these fundamental questions, if conditions are inadequate for the purpose desired, is the question, what can reasonably and economically be done to improve these conditions? In the solution of the major engineering problems associated with the Columbia Basin Project as it concerns the Nespelem clays, the first question has been answered by the reply, completely inadequate, and the second question has been answered by the "rule-of-thumb" previously

delineated. This has inevitably led to propounding the fourth question over and over again for each structure or part of a structure in which the Nespelem sediments were involved.

Traditionally, the stability of slopes has been improved by one or more of three methods; adding support at the toe, unloading the upper parts of the slope, or unwatering the body of the material. Each of these methods has been employed at some parts of the area, but space limitations, the high cost of producing sufficiently flat slopes, and the impermeability of the varved clays have prevented their general application. Four additional principles have therefore been added. These are: (1) convert the fluid in the slide material to a less detrimental state; (2) relocate the structure to minimize the influence of detrimental materials; (3) minimize the disturbance to the natural conditions; and (4) utilize the natural conditions available to improve the site.

Grand Coulee Dam Foundations

It should be obvious that the 550-foot-high Grand Coulee Dam could not be founded in any part upon the varved clays and that their complete removal from beneath the dam was essential. The removal of these materials immediately introduced the problem of selecting sufficiently stable slopes to allow the base of the dam to be constructed. Laboratory tests have indicated that these varved clays are approximately three times as strong in their undisturbed state as in the reworked state and temporary excavations might therefore be made with normal slopes that would be reasonable in cost if disturbance could be avoided. The central portion of the river section requiring cuts up to 30 feet deep was successfully handled in this manner. On the left abutment where the Nespelem formation was up to 300 feet thick and had had its continuity destroyed by many old slides, the situation was handled by allowing slides to develop and treating the area in the traditional manner, weighing and supporting the toes of the excavation, drainage, and flattening the slopes. Generally, the depth to bedrock on the right abutment was small and excavation was accomplished without difficulty since the overburden was mainly sand and gravel. However, at the base of the right abutment the sand and gravel was underlain by varved clay and a deep ravine was found paralleling the river that, although only about 100 feet wide, also extended to a depth of more than 100 feet below the general level of the bedrock.

Excavations in the clay-filled ravine were first started following the same practices that had been used at the left abutment. A 1-1/2:1 slope proving to be unstable, and the excavation slope was flattened to 2:1. At this slope the excavation was extended to bedrock. Since it appeared that this slope could not be maintained long enough to construct the foundation of the dam, a concrete retaining wall was built in the ravine. A timber crib wall was in process of being built when the slide became active completely overflowing these structures and filling the excavations.

High water prevented further work in this area until the Fall of 1936. Meanwhile, the upper part of the excavation was flattened to a slope of between 2-1/2 and 3:1, but as the water level in the river receded the slide again became active. It now appeared that the materials had

become so disturbed that most of the original strength was lost and that slopes of 4 or 5:1 would be needed. The ravine itself being quite narrow contained only a small volume of material, but its removal would allow the Nespelem clays from both sides to flow into the excavation so that the necessary slope flattening might ultimately require the removal of several million cubic yards of material. While contemplating this problem, the idea was first conceived of freezing the water in the soil and thereby strengthening the mass sufficiently to allow the excavation quantities to be reduced to a reasonable volume.

The idea of refrigerating soils to improve their strength was not new having been used previously in sinking shafts and wells but no previous experience existed on such a large scale. Studies of the conditions in the area indicated that the recent slides had become stabilized and that they would not become active until excavation below elevation 855 was undertaken. This fixed the upper level to which the frozen section needed to extend. If a dam of frozen material of sufficient strength could be developed, the amount of freezing could be minimized. The narrowness of the ravine and the timber crib on top of the concrete retaining wall could be used in conjunction with a frozen arch dam to provide support of the slide with a 40-foot-high dam. The details of this construction including the results of tests may be found elsewhere[3], [4] and need not be repeated here.

The cost of this structure at the economy level of 1936, when it was built, was approximately $50,000 and its construction reduced the amount of excavation costs of even the most optimistic procedure by at least $30,000 and in addition prevented a slide of major proportions into the excavation. It must have been many times cheaper than if conservative excavation slopes had initially been used. However, this is not a method recommended for general use as it is probable that the construction and maintenance for one year of a frozen section of similar magnitude in 1952 would cost in the order of $40 per cubic yard. It does, however, demonstrate the benefits to be achieved from a careful analysis of the foundation condition existing at the site of a major structure and the application of ingenuity to its solution.

North Coulee Dam Foundations

The second instance in which a thorough knowledge of the character of the foundation was used to develop both a safe and economical design in which a knowledge of the character of the Nespelem formation was utilized occurred at North Coulee Dam.

The plan of development for the irrigation facilities of the Columbia Basin involve a pumping plant to lift water from Lake Roosevelt up to Grand Coulee which is dammed at both ends to provide both a reservoir and a conveyance system to the irrigable lands to the south and west. North Coulee Dam forms the northern closure of the reservoir. In the

3. "The Use of Refrigeration in Building the Grand Coulee Dam," by Grant Gordon, Refrigerating Engineer, Volume 33, 1937.
4. "Frozen Earth Dam at Grand Coulee" by Lloyd V. Frorge, Mechanical Engineering, January 1941.

area where the dam was to be located the Columbia River during the glacial period had cut through the Columbia River basalt beds and the interbedded Latah shales and into the basement Coleville granites. The lowest part of the gorge had been refilled with pervious gravel and boulders overlain by disturbed Latah shale and basalt boulders that resulted when portions of the oversteepened side walls of the Coulee sloughed into the valley. This condition in turn was blanketed with a layer of the Nespelem sediments during the last stages of glacial action previously described.

The minimum section topographically resulted from the juxtaposition of a high ridge in the basal granite on the right and a large migrant basalt mass on the left. The gorge in between, about 85 feet deep, was filled with Nespelem sediments and topped with swamp muck.

Concern that the basalt mass might subsequently move when the reservoir was filled and the large amount of excavation involved in providing an acceptable foundation for an earth dam led to extensive explorations elsewhere in the Coulee for a more economical dam site. Although improved foundations could be located, the greater volume above ground repeatedly indicated that the initial site would be most economical if reasonable slopes could be maintained in the Nespelem silts.

Extensive explorations laterally from the axis of the dam to determine the character of the Nespelem sediments disclosed a rapid rise in the floor of the Nespelem deposit in a northward direction. Comparative estimates indicated that a minor relocation in an upstream direction could result in a marked reduction in cost for the structure and at the same time would reduce the work required. By shifting the location of the cut-off trench at the same time, the total depth of excavation could be reduced to about 40 feet.

The Nespelem sediments in the vicinity of the North Dam were poorly consolidated, not having had the loading of the overriding glacier experienced elsewhere and the upper part of the deposit had been reworked by wind action to give this part of the deposit the general character of loess, a set of characteristics completely different from the varved clays. The lack of consolidation in these sediments led to selection of a section with a wide bottom cut-off to support the central section of the dam, low angle slopes in the cut-off trench to distribute the differential settlement as well as to provide greater safety in excavation of the trench and extensive toe supports constructed out of the materials from the excavation. This also simplified the disposal problem.

Upon excavating into these deposits, it was found that the Nespelem sediments contained many large basalt masses up to 20 cubic yards in volume that made unwatering very difficult and the flat slopes adopted for the excavations imperative.

The situation described at North Coulee Dam has been observed so frequently at other dam sites as to make its consideration almost standard procedure. The natural conditions that produce the valley restrictions that indicate favorable dam sites frequently result in deep foundations refilled first with pervious materials and then progressively with finer and less consolidated, structurally weak deposits. The treatment of these conditions is often more expensive than if the site is shifted to reduce foundation treatment even though the embankment volume is

increased. The relocation that resulted from thorough investigation of the foundation in this instance resulted in a reduction in the cost of the structure by about 25 percent.

Feeder Canal to the Upper Coulee Reservoir

Another example of the value of careful appraisal of the geologic history of an area which demonstrates the use of the procedure for minimizing the disturbance of the natural conditions is thought to be of sufficient interest to warrant mention here, although the materials involved are the Latah shales rather than the Nespelem varved clays. The problem involves the construction of the canal between the pumping plant and the reservoir. A portion of the canal traverses the western side of the Coulee along moderate cross slopes in the Latah shale and among a number of migrant blocks of basalt. The Latah shale is generally a flat-bedded, moderately compact sandy shale with some pure sand to silty sand phases in the formation, but generally lacking in features that would make its stability questionable. Initial designs contemplated a lined canal since seepage in such materials was expected. When excavation was started in one section of the canal, the uphill slopes began moving as soon as a short reach of canal was completed. Further analysis of the area showed a high and steep water table that could not practicably be relieved. Attempts at reducing slopes indicated that natural slopes would essentially have to be reproduced before stability could be achieved which in turn would have undermined several large basalt blocks. The use of a cut and cover conduit was therefore adopted. In this section of the canal short reaches were excavated, the conduit poured, and the ground restored to the original slopes before the next section was started. Sections, 150 feet long, were completed satisfactorily in this way. An extensive drainage system was installed under the conduit to control leakage from the joints and also to keep the water table down so that natural slides would be minimized.

The use of slopes approximating those proved to be safe under natural conditions is finding increasing application, making the use of such alternative treatments as cut and cover sections or tunnels competitive in many locations. In the instance cited above, it proved to be a most economical, even if expensive, solution.

Stabilizing the Tailrace Area

Our most recent problem involving the varved clays concerns the slopes on both sides of the tailrace area. Terrace lands adjacent to the tailrace channel provide a most attractive area for the location of both the operating and construction camps. Much of the construction originally intended to be purely temporary has of necessity become permanent. In addition, many operating facilities, switchyards, shops, and roads have been located in these areas to such extent that the prevention of slides has become imperative.

The first approach consisted of flattening the slopes in these areas and protecting the underwater slopes with riprap. Stability analyses using average values determined from laboratory tests showed the resloped areas to be amply stable, but small fluctuations in river level

appeared to result in minor movements with cracks and displacements varying from a few inches to several feet. Subsequently, the toes were covered with additional rock fill some of which was displaced by the 1948 flood flows. Believing that progressive undercutting would produce additional slides, most of the critical areas have been paved with a layer of armor rock up to 5 tons in weight and as a further precaution drainage of the areas was recommended. Drainage tunnels had previously been constructed on the left bank and explorations were initiated to locate a tunnel on the right or west side.

The underground explorations revealed that the area had been extensively disturbed, but did not reveal marked planes of weakness. The water table was persistently high with seasonal variations, but over a buried ravine such as caused so much trouble during the construction of Grand Coulee Dam, there appeared to be a dip in the water table. A water table map of the west tailrace area shows the water table to follow the configuration of bedrock rather than the surface. That such a condition could persist, that is an isolated high ridge of water with no source of supply, seemed highly improbable, therefore, the area was carefully investigated with special attention given to water levels as the drill holes were deepened. Some holes penetrated water bodies under pressure; in others a comparatively high water level fell markedly when the holes were deepened. The foundation investigation indicates that the granite bedrock found about 60 feet below the surface at river level rises gradually for about 500 feet until the depth of varved clays increases to about 90 feet. Bedrock then rises to the ridge separating the river and the ravine. Beyond the ravine bedrock rises steeply to the surface about a quarter mile from the river. The Nespelem varved clays overlay bedrock except in the bottom of the ravine where a thick layer of gravel and boulders is found. Gravel and sand beds next to the canyon wall interfinger into the upper parts of the varved clay beds.

It is hypothecated that the upper sand and gravel beds provide a path for saturating the varved clays. The gravels within the ravine provide a path for draining this water near the point of intake, but the laminar nature of the deposit prevents this drainage from being effective. It is believed that slides are induced by a sudden drop in river water level when the water table in the varved clays is high. Gradual lowering of the river allows sufficient drainage from the varved clay zone to prevent slides or a low water table in the varved clays induces sufficient added strength so that slides are prevented even with rapid river lowering.

To maintain stability, river flows are therefore being maintained to prevent a greater fluctuation than 4 feet in 24 hours. In the Fall and Winter of 1951, this requirement prevented the full utilization of the power plant in meeting peak power demands. In an attempt to relieve this situation the record of river levels, ground-water levels in the tailrace area, and slides are in process of being studied. A test installation has been made, which is now under study, attempting to prevent saturation of the varved clays by diverting the water from the Nespelem beds into the gravels of the ravine through a series of wells. The initial data indicate that this system will be effective.

Making use of a natural situation found at the site will eliminate a

requirement for an expensive drainage tunnel with a potential saving in cost of several hundred thousand dollars. Without an extensive investigation and a thorough study of the data requiring many months of work, this possibility would certainly have been overlooked.

CONCLUSIONS

The development of a knowledge of the natural conditions surrounding the Nespelem varved clays and their influence on performance has been a slow and difficult process. That it has largely been by trial and error particularly during the earlier stages of construction of the Columbia Basin Project has not been so much due to oversight as it was due to the overshadowing of these problems by the far greater problem of designing a project of such magnitude. The problems associated with varved slays are only a small part of the many varied situations that required investigation, analysis, and solution in the development of this project. Nor are the few problems here described more than a brief taste of all the difficulties experienced in working with the Nespelem varved clays.

These instances are sufficient, however, to demonstrate the wide range that engineering solutions may take in dealing with a single geological condition. They should also serve to emphasize the benefits to be achieved from a thorough comprehension of the geological condition in the solution of many engineering problems. Although the specific answers developed here are of limited application, the procedures used of first learning the general geological situation at the site followed by preparing a tentative engineering solution for which the geological conditions are developed in detail and from which the final engineering solution is obtained, should find widespread application in the coming century as it already has by the Bureau of Reclamation.

The still too frequent custom of designing engineering structures strictly by precedent would have proved to be both impractical and too expensive when dealing with the Nespelem varved clays. The practice of applying only the results of laboratory tests to theoretically developed analyses to obtain a solution to such problems has been shown to be equally unsatisfactory. The only satisfactory procedure has proved to be a discrete application of both methods to a complete set of data by a process of thorough rationalization.